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On the compressional rheology of fresh faeces: Evidence for improving community scale sanitation through localised dewatering

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ABSTRACT

Non-sewered sanitation is currently dependant upon pit latrine emptying, the safety of which is compromised by the high costs of faecal sludge transport to centralised treatment facilities. Transport in turn is hindered by the complex rheology of pit latrine sludge. This study therefore characterised the compressional rheology of fresh faeces and modelled the implications for passive (gravity) or mechanical (forced) solid/liquid separation. This informs on the viability of decentralising dewatering for more efficient volume reduction and improving the economics of transportation. The gel point (ϕ_g) is the solids concentration where the material has a networked structure and signifies the point when mechanical intervention is required for further solid-liquid separation. For fresh faeces, ϕ_g ranged between 6.3 and 15.6% total solids (TS) concentration. This is significantly higher than the ϕ_g observed for wastewater sludge at centralised facilities, and it implies that passive gravity driven processes can suffice to improve localised dewatering. The kinetics of passive sedimentation of faecal material were modelled and illustrate thickening from 3 to 10% TS concentration in <0.5 h. This highlights that early intervention to thicken faeces while fresh can improve solid/liquid separation efficiency. Filtration of fresh faeces was characterised by lengthy cake filtration times and comparably short compression times, more similar to mineral slurries than to wastewater sludge. Consequently, fresh faeces presented improved dewatering characteristics, supporting higher final cake solids concentrations and improved dewatering kinetics. By complementing thickening with 300 kPa filtration, a 1.4 cm thick 25% TS product could be achieved in <24 h. Investigation of matrix properties highlighted that increased conductivity (e.g. exposure to urine) negatively influenced dewaterability, an effect which could be mitigated by introducing solid-liquid separation earlier. The thermodynamically favourable compressional rheology of fresh faeces has identified that focussing on localised dewatering could radically improve the economics of faecal sludge management, primarily through reducing transport costs.

1. Introduction

Non-sewered sanitation solutions such as pit latrines and septic tanks serve one third of the world's population, acting as an affordable alternative to conventional wastewater treatment. These systems function as intermediate storage facilities, requiring emptying and transport to centralised facilities for safe treatment. Simple thickening and dewatering processes, such as drying beds, are generally used to minimise sludge volume through removing excess water, before the faecal sludge can be applied to downstream processes (Tayler, 2018). Dewatered solids can then be dried or pasteurised for safe environmental disposal (Brockmann, 1973; Naidoo et al., 2020; Septien et al., 2018b). However, in the urban setting, only 22% of pit latrine sludge is safely managed (Blackett et al., 2014), leading to enteric pathogenic contamination of community water resources, resulting in diarrhoea responsible for the highest illness and morbidity rates worldwide (UNICEF and WHO, 2015). With safely managed sanitation practices, it is projected that up to 88% of diarrhoea related deaths could be prevented (UNICEF and WHO, 2015).

The emptying and transport stages represent significant inhibitors in the faecal sludge management chain, due to the difficulty of mixing and pumping aged compacted sludges, reported to have densities of up to

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1750 kg m^{-3} (Radford and Sugden, 2014). High water volumes are added to dilute sludge to over 95% water to enable emptying via pumping (Basamykina et al., 2020; Gold et al., 2016; Septien et al., 2018a; Strande et al., 2014). This practice economically compromises the transport stage, estimated to represent 25% of faecal sludge management costs (Steiner et al., 2002). Multistage transport is frequently practiced in urban areas with sludge transferred via small capacity vehicles to sludge storage stations, onto larger tankers and then transported for disposal or treatment (Mikhael et al., 2014). Such transport practices also require multiple pumping stages to transfer silted sludge between stages, incurring further costs (Mikhael et al., 2014). This extended, complex and intensive transport practice represents one of the key challenges to achieving the Sustainable Development Goals (SDGs) of safely managed sanitation for all by 2030 (United Nations, 2018).

One approach to resolving the challenge of sludge transport in faecal sludge management is to intervene at community scale by locally dewatering fresher unconsolidated faecal sludge, with a focus on reducing sludge volume whilst also transforming its rheological properties into an easier to handle material (e.g. a dry friable product). This improves the economics of emptying and transport, as well as reducing pathogenic risk (Brockmann, 1973; Naidoo et al., 2020). Also, the nutrient and organic rich solid fraction could provide local economic opportunities for nutrient or energy recovery (Eshetu Moges et al., 2018; Forbis-Stokes et al., 2016; Harder et al., 2019; Onabanjo et al., 2016). As such, small footprint community based intervention strategies that reduce emptying and transport fees could enable a shift towards sustainable faecal sludge management (Mikhael et al., 2014).

To facilitate decentralised solid/liquid separation at community scale and within densely populated areas, mechanical dewatering technologies such as centrifuges and mechanical presses, more commonly applied for municipal wastewater sludges (Novak, 2006), provide a low footprint, high efficiency alternative to the currently adopted large scale, long duration drying beds (Basamykina et al., 2020; Gold et al., 2016). Such modularity allows for adaptation to population growth, which is predicted to reach 9.8 billion by 2030 (Hilal and Wright, 2018; United Nations, 2017). However, organic rich faecal sludges, whether encountered in centralised municipal wastewater facilities or decentralised sanitation infrastructure, are recognised as difficult to dewater, which could compromise economic feasibility (Gold et al., 2018; Semiyaga et al., 2016; Skinner et al., 2015; Ward et al., 2019). Poor dewaterability for wastewater sludges is often associated with hydrolysis mechanisms under long-term storage, as well as exposure to viscous shear during transport (Christensen et al., 2015). The impact of storage time and shear on dewaterability of faecal material specifically is not yet elucidated. However, there may be potential advantages to rejecting faecal sludge storage and instead focussing on concentrating fresh faecal material, which has been subject to less dispersion by shear history or hydrolytic effects. To the best of the authors' knowledge, the dewaterability of fresh faeces has yet to be characterised.

Conventional methods to determine the dewaterability of faecal matrices such as municipal wastewater and non-sewered sanitation sludges, are based on empirical techniques such as capillary suction time and single pressure filtration or centrifugation tests that provide the rate and extent of dewatering respectively (Chen et al., 2010; Gold et al., 2018, 2016; Liu et al., 2013; Semiyaga et al., 2017; Ward et al., 2019). These tests provide a relative comparison between material properties, but they are not sufficiently rigorous to enable dewatering technology design (Chen et al., 2010; Gold et al., 2018, 2016; Liu et al., 2013; Semiyaga et al., 2017; Ward et al., 2019). The design and operation of dewatering processes requires that material dewaterability is described as a function of solids concentration and applied pressure. Compressional rheology, first described by Buscall and White (Buscall and White, 1987), provides a phenomenological approach to solid/liquid separation where the compressive strength (P_y, compressive yield stress) and rate of dewatering (inversely related to hindered settling function, R) of a networked matrix are functions of solids concentration. In this description there is a critical solids concentration known as the gel point (ϕ_g). This is the minimum solids concentration at which the suspended solids particles form a continuously networked structure with an inherent strength or yield stress. The compressive yield stress (P_y) is the pressure required for the networked solids matrix to yield and compress. P_y is a strong function of solids concentration, varying from zero at ϕ_g and rising exponentially as the solids concentration increases. The hindered settling function (R) is defined as a resistance of liquid to flow around the solid particles at low solids concentrations and through the solids network structure at higher solids concentrations. R varies exponentially, increasing by 8–16 orders of magnitude from low to high solids concentrations. These physical properties define dewaterability aspects of a particulate matrix. These material properties have been previously used to characterise compressible inorganic matrices (de Kretser et al., 2001; Usher, 2002; Usher et al., 2001), water treatment sludges (Harbour et al., 2004; Stickland et al., 2006) and wastewater sludges (Scales et al., 2004; Skinner et al., 2015; Stickland, 2015; Stickland et al., 2008; Studer, 2008; Wall, 2008). In this study, this phenomenological approach is applied to characterise the compressional rheology of fresh faeces, to inform on the practical viability of decentralising dewatering assets for the improvement of community scale faecal sludge management. Specific objectives are to: (a) determine the gel point (ϕ_g), compressive yield stress (P_y) and hindered settling function (R) of fresh faeces to develop a complete description of faecal material dewatering; (b) diagnose dewatering data using municipal waste activated sludge and mineral slurry as compressible reference materials, with acknowledged distinctions in dewatering characteristics; and (c) investigate the role of several unique suspension characteristics (Bristol Stool Scale, coarse particles (i.e. fibre) and conductivity) which are thought to influence suspension dewaterability. Finally, compressive yield stress and hindered settling function characterisation data are used to model passive gravity thickening (Bürger and Hvistendahl Karlsen, 2001; Spehar, 2014; Usher and Scales, 2005), centrifugation (Bürger and Concha, 2001; Usher et al., 2013) and filtration processes (Stickland et al., 2006) to confirm the feasibility of community scale dewatering interventions through a breadth of technical approaches.

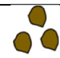
2. Materials and methods

2.1. Collection and characterisation of fresh faeces and urine

Faeces sampling: Faecal samples were collected from consenting anonymous volunteers through a regime approved by the Cranfield University Research Ethics System (CURES, project ID 8488). Faeces were categorised into stool types according to Bristol Stool Scale (BSS 1–7), as described by Heaton et al. (1992, Table 1). Types 1–3, which represent hard dense lumps (BSS 1), lumpy sausage (BSS 2) and cracked sausage (BSS 3), were combined due to low sample masses. Diarrhoea (BSS 7) was not encountered during sampling. Type 4, which is shaped as a smooth sausage, is the most frequent faecal type (Heaton et al., 1992). This was hence selected as a control to investigate the impact of big undigested food particles through the use of maceration and to assess the role of conductivity by combining faeces with urine. Blackwater samples were prepared by combining urine with BSS 4 faeces, briefly mixing (1000 rpm, 30 s) with a *Haake Viscotester iQ rheometer* (Thermo Electron, Karlsruhe, Germany) with a FL22 4B/SS vane. For analysis of maceration impact, samples were processed at 3000 rpm for 30 s using an *IKA T50* digital Ultra-Turrax homogeniser with a *S50N-W65SK* cutting head (IKA® England LTD, Oxford, UK). Faeces and urine samples were sealed and stored at 4 °C with physico-chemical analysis completed and dewaterability tests initiated no more than a week after collection to maintain freshness.

Faecal liquid fraction: In order to characterise the dewaterability of faeces across a range of solids concentrations, the faecal liquid fraction properties ('faecal liquor') were required to calculate particle

Table 1
Stool types as described by Heaton et al., (1992).

Bristol Stool Scale (BSS)	Description	
BSS 1		Hard dense lumps
BSS 2		Lumpy sausage
BSS 3		Cracked sausage
BSS 4		Smooth sausage
BSS 5		Soft defined blobs
BSS 6		Mushy stool
BSS 7		Watery, no solid pieces

interactions at different solids concentrations. Due to the high solids content of faeces, extracting sufficient liquor from individual samples was not viable. Therefore, six faeces samples representing BSS 1–6 were centrifuged at 5000 rpm for 12 h (*Sorvall Legend RT*, Thermo Scientific, Loughborough, UK) to extract sufficient volume to determine the general faecal liquor properties (summarised in Table S1). As a substitute for faecal liquor, dilution of faeces was carried out by using a saline solution of the same conductivity (7.61 g L^{-1} NaCl, 12.62 mS cm^{-1}). This was to prevent cell lysis from osmotic pressure. A liquor substitute was similarly utilised and verified by Stickland et al., (2008) for wastewater liquor. All but one sample were diluted with the saline solution. Urine was used instead of the saline solution to dilute faeces when determining the impact of a blackwater matrix on faeces dewaterability (Sample BSS 4 Urine, Table S2).

Physico-chemical characterisation: Further properties of the faecal samples were measured to diagnose the dewatering behaviour of different sample types. These included the determination of extracellular polymeric substances (EPS) through protein and carbohydrate concentrations and chemical oxygen demand after a 0.2 μm filter ($COD_{soluble}$). Protein concentrations were measured using the modified Lowry method (UV750 nm) (Lowry et al., 1951) with bovine serum albumin (BSA) (Sigma-Aldrich, UK) as the standard. Carbohydrate concentrations were measured using the Dubois phenol sulphuric acid method (UV490 nm) (Dubois et al., 1956) with glucose (Sigma-Aldrich, UK) as the reference standard. Quantification of protein and carbohydrates was achieved by spectrophotometry (*NOVA60* photometer, VWR, UK) and chemical oxygen demand was analysed using a Merck vial test kit (Merck KGaA, Darmstadt, Germany). Undiluted faecal samples were first prepared by combining 5 g of undiluted faeces in 50 mL of deionised water. Conductivity was obtained using a probe (*Jenway 4330*, Cole Parmer, Staffordshire, UK). Particle size distribution of pre and post macerated faeces involved filtering the sample through gradation sieves with mesh sizes of 1, 2, 3.35 and 4.75 mm, to capture the macro-particle fraction.

Total solids (TS), volatile solids (VS) fraction of TS, total suspended solids (TSS) and liquor dissolved solids after filtration (DS), were determined using standard wastewater methods (APHA, 2012) and used to calculate the solids volume fraction (ϕ) according to Appendix A. All dewatering calculations and modelling were performed with solids concentration represented on a volumetric basis as solids volume fraction (ϕ).

2.2. Gravitational batch settling tests

Transient batch settling tests, tracking the sediment-liquid interface height over time, were analysed based on a previously verified method (Lester et al., 2005; Usher et al., 2013) using a Kynch (1952) type analysis to determine settling velocity (u, m s^{-1}) as a function of solids concentration. The hindered settling function (R) is determined from the settling velocity using the following relation:

$$R(\phi) = \frac{\Delta\rho g(1-\phi)^2}{u(\phi)} \tag{1}$$

where $\Delta\rho = \rho_{solid} - \rho_{liquor}$ is the solid-liquor density difference, u is the settling velocity (m s^{-1}) and g is gravitational acceleration (m s^{-2}). The final equilibrium sediment height is used in the determination of ϕ_g and P_y(TS) near ϕ_g (Lester et al., 2005; Stickland, 2015; Usher, 2002) such that the final average solids concentration (ϕ_{av}) provides an estimate of the gel point:

$$\phi_g \approx \phi_{av} = \frac{\phi_0 h_0}{h_\infty} \tag{2}$$

where ϕ_0 and h_0 are the initial solids volume fraction and height, while h_∞ is the final equilibrium height.

Between 40 to 60 g of a fresh sample were briefly mixed at 1000 rpm for 30 s using a *Haake Viscotester iQ rheometer* (Thermo Electron, Karlsruhe, Germany) with a FL22 4B/SS vane and diluted within 500 mL of the saline solution or urine (BSS 4 urine) in a glass measuring cylinder. The cylinder was sealed with parafilm and turned upside-down to re-suspend the matrix before starting the test. As soon as the cylinder was upright, the change in sediment-liquid interface height was recorded over 48 h until the height stabilised.

2.3. Stepped pressure filtration

Mechanical intervention is required to overcome network stress and enable dewaterability characterisation at solids concentrations well above the gel point. Constant pressure filtration techniques were developed by Landman and White (Landman et al., 1995; Landman and White, 1997) to quantify P_y and R at solids concentrations exceeding ϕ_g, using a series of single pressure filtration tests at different pressures. Each test requires more of the same sample, which for faeces is limited and is susceptible to changes in physico-chemical properties over the extended time periods between tests. In order to decrease characterisation time, de Kretser et al., (2001) and Usher et al., (2001) optimised and validated a stepped pressure filtration method, where multiple pressures can be characterised in two experiments – a permeability test and compressibility test. For stepped pressure filtration tests, this study has utilised an automated filtration rig comprised of an analogous design (Fig. S1(b)). The rig was controlled and data analysed using the accompanying LabVIEW software.

In a compressibility test, a piston applies a constant pressure (ΔP) onto a suspension contained within a compression cylinder at initial solids volume fraction (ϕ_0) and initial height (h_0). Liquid permeates through a porous membrane at the base of the cylinder where a cake builds until it reaches the piston face and then consolidates to the maximum solids concentration $\phi_\infty = \phi_0 h_0 / h_\infty$ where $P_y(\phi_\infty) = \Delta P$, such that h_∞ is the final equilibrium height. The pressure is then stepped and the material consolidated to equilibrium at a number of pressures (Fig. 1a).

In a stepped pressure permeability test, the slope $dt/dV^2 = 1/\beta^2$ during bed formation is determined for a number of pressures (ΔP) where the operational parameters time (t), specific filtrate volume (V) and filtration parameter (β^2) are recorded. Each pressure is stepped once a stable slope is reached (Fig. 1b). The hindered settling function (R) is then calculated using the gradient of a curve fit of β^2 vs. ΔP and the ϕ_∞ values from the compressibility tests using the following equation:

$$R(\phi_\infty) = \frac{2}{\left(\frac{d\beta^2}{\Delta P}\right)}\left(\frac{1}{\phi_0} - \frac{1}{\phi_\infty}\right)(1-\phi_\infty)^2 \tag{3}$$

Another section of the same faeces sample used for the batch settling test was simultaneously characterised in the filtration tests. Faecal samples were briefly mixed (1000 rpm, 30 s) with the saline solution or urine at a 1:2 faeces to solution (w/w) ratio to nominally represent the gel point of the samples. This was performed using a *Haake Viscotester iQ rheometer* (Thermo Electron, Karlsruhe, Germany) with a FL22 4B/SS vane before subjecting samples to filtration. This sample preparation was critical to avoid air gaps and allow for a uniform volume (50 mL) when loaded into the filtration rig. Based on previous evidence, the short mixing time imparted insufficient shear to disrupt the coarse particle structure during sample preparation (Ravndal et al., 2019). The quicker permeability test was always conducted first on a sub-sample, as it allowed for the subsequent compressibility test to start less than a week after sample collection on another sub-sample, maintaining faeces freshness. Different pressures for both tests were tested within the same sub-sample, as the stepped pressure filtration rig allowed for a change in pressure without opening the system. Both compressibility and permeability tests were programmed with set pressures of 20, 50, 120 and 300 kPa. The final cake height was consistently higher than the recommended minimum of 5 mm, ensuring that the linear encoder resolution of 10 μm did not compromise accuracy (de Kretser et al., 2001; Usher et al., 2001) and also ensuring that coarse chunks of material are less likely to compromise tests by bridging between the membrane and the piston. Verification of method accuracy prior to completion of analysis was conducted with a BSS4 macerated sample, for which TS values at 50 kPa (P_y(TS) = 50 kPa) varied by <3.8% TS between replicates and gel point <1% across replicates.

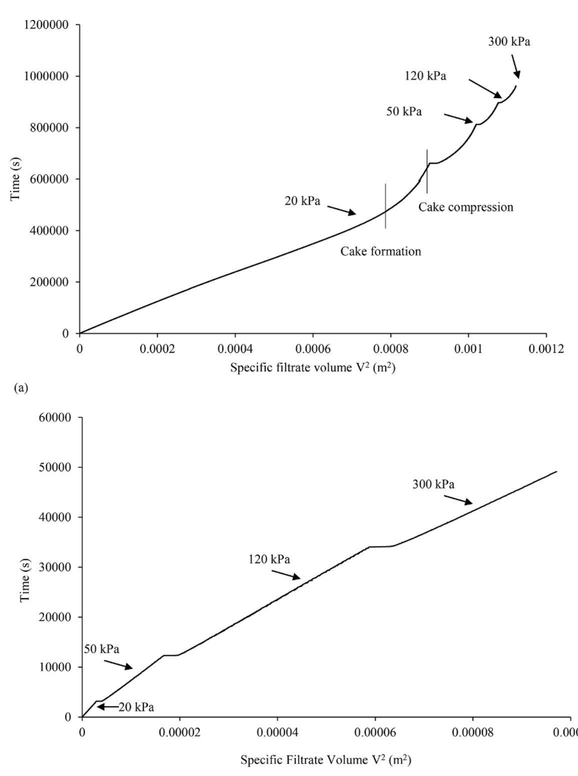


Fig. 1. Example of (a) compressibility and (b) permeability test time (t) vs. specific filtrate volume squared (V^2) filtration plot data obtained from the stepped pressure rig.

2.4. Combining data into curve fits

The compressive yield stress (P_y) data from filtration tests were fitted to a functional form described by Lester et al., (2005) and then ϕ_g, initially estimated using Eq. (2), was adjusted until the compressive yield stress curve was exactly consistent with the final height of the settling test (see(Crust, 2017) for details).

The hindered settling function (R) data from both settling and filtration tests were combined and fitted using an interpolation function over the full range of solids concentration data from the initial settling test concentration to the final concentration achieved at the highest filtration pressure. The data were exponentially extrapolated outside this range for very low and very high solids concentrations. P_y and R curve fits were then combined into a single term known as the solids diffusivity (D) to illustrate the overall dewaterability (Landman et al., 1995):

$$D(\phi) = \frac{dP_y(\phi)}{d\phi}\frac{(1-\phi)^2}{R(\phi)} \tag{4}$$

where ϕ is the solids volume fraction.

2.5. Modelling

Process modelling was conducted to compare the predicted dewatering performance of faeces, against wastewater sludges (Skinner et al., 2015) and mineral slurry (Usher et al., 2013) literature data in passive gravity settling, and mechanical units (e.g. centrifugation and filtration). The one-dimensional differential equation that describes these processes in linear coordinates is given below (Landman and White, 1994):

$$\frac{\partial\phi}{\partial t} = \frac{\partial}{\partial z}\left[D(\phi)\frac{\partial\phi}{\partial z} + \phi.u(\phi)\right] \tag{5}$$

Where ϕ is the solids volume fraction, t is time, z is a length coordinate such as height, $D(\phi)$ is the solids diffusivity function defined above in Eq. (4) and $u(\phi)$ is the settling velocity function related to the hindered settling function, $R(\phi)$ by Eq. (1). A range of initial solids concentrations (TS = 0.1, 1, 3, 10 and 25% TS) were used with initial saline diluted faeces heights (h_0 = 350, 35, 11.7, 3.5 and 1.4 cm) where all scenarios used the same amount of solid material (nominally 1 cm at 35% TS). For example, if the initial solids concentration is 10% TS, the initial height scales to 3.5 cm. The relevant sediment and piston heights were predicted as a function of time until no more dewatering could occur. From these heights, the average solids concentrations were calculated and graphed to show the influence of the material, initial solids concentration and dewatering method on the rate and extent of dewatering.

The passive gravity batch settling predictions used a semi-implicit finite difference algorithm to numerically solve a second order discretisation of Eq. (5) to predict the solids concentration distribution as a function of time. The algorithm simulated a simple 1-D batch settling scenario, with the sediment-liquid interface height (h where $\phi = \phi_0$)

recorded until sedimentation and consolidation of the networked bed ceased at an equilibrium solids concentration distribution. The method has been previously validated by Usher et al., (2006), is detailed in Spehar (2014) and was adapted from algorithms described by Burger and Karlsen (2001). The number of height elements used in the computations varied from 50 to 1600 to balance computation time and accuracy.

The centrifugal settling predictions used a semi-implicit finite difference algorithm to numerically solve a discretised radial coordinate variant of Eq. (5) over time. The algorithm simulated a 1-D batch centrifugation process for a thin tube with an outer radius (r_{max}) of 0.25 m and a rotation speed of 1000 rpm with the sediment-liquid interface height ($h=r_{max}-r$ where $\phi=\phi_0$) recorded over time until equilibrium. The number of elements used in the computations varied from 50 to 1600 to balance computation time and accuracy. The method is described in Usher et al., (2013) and was adapted from algorithms developed by Bürger and Concha (2001).

The filtration modelling predictions used a Runge-Kutta algorithm to numerically solve a simplified discretisation of Eq. (5) over time with a moving boundary condition and gravity removed such that:

$$\frac{\partial\phi}{\partial t}=\frac{\partial}{dz}\left[D(\phi)\frac{\partial\phi}{\partial z}\right] \quad (6)$$

Where ϕ is the solids volume fraction, t is time, z is a length coordinate representing distance from the filter cloth, $D(\phi)$ is the solids diffusivity function defined above in Eq. (4). The algorithm simulated a 300 kPa pressure in a 1-D batch filtration process where the material is consolidated over time by movement of a piston towards a membrane permeable to liquor but not to suspended solids. The piston-membrane gap (h) is recorded over time until consolidation ceases at equilibrium. The algorithm was developed, described and validated by Stickland et al., (2006).

3. Results and discussion

3.1. Comparison of fresh faeces dewaterability to other compressible matrices

To characterise the compressive yield stress (P_y), hindered settling function (R) and solids diffusivity (D), curve fits were produced by combining settling data at low solids concentrations with pressure filtration data from high solids concentrations (Stickland et al., 2008; Skinner et al., 2015). Data was first interpreted using suspended solids volume fraction (ϕ) in accordance with the analytical approach proposed by Buscall and White (1987), but are presented as total solids fractions on a mass basis (TS) as this parameter is more commonly employed to characterise wastewater suspensions. The gel points (ϕ_g) of fresh faeces were determined to have TS concentrations of 6.2, 7.2, 13.9 and 15.6% for Bristol Stool Scales of 6, 5, 4 and 1–3 respectively (Fig. 2, Fig. S1(a)), where BSS1–3 was physically characterised by a consolidated structure, and BSS6 a mushier stool, tending toward diarrhoea (Table 1). These TS concentrations represent the point at which these suspensions form an inter-connected particle network capable of supporting their own weight (Harbour et al., 2001). Dewatering data of thickened waste activated sludge (TWAS) (81% VS), obtained from Skinner et al., (2015), was overlaid to compare the dewatering behaviour of fresh faeces and that of sludge from centralised infrastructure. The gel point for TWAS was 2.4% TS, which is comparable to literature (2–3%; Pileggi et al., 2019). The lower ϕ_g of waste activated sludge is generally attributed to the density of intact bacterial cells that introduce a relatively high EPS fraction, creating a heterogeneous stable colloidal complex which may promote the early onset of networking (Christensen et al., 2015; Zhou et al., 2017).

For TS concentrations exceeding ϕ_g, the network strength is sufficient to exhibit a yield stress (Harbour et al., 2001) once subjected to an

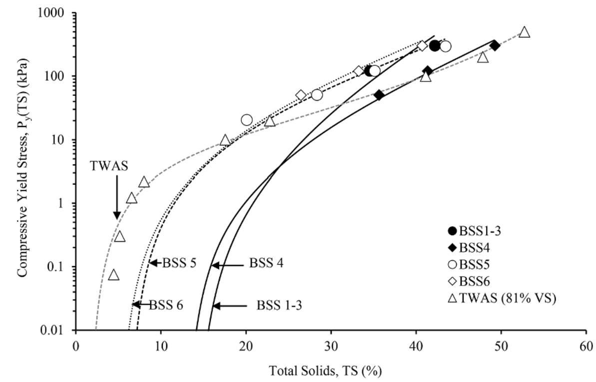


Fig. 2. Compressional rheology behaviour expressed as compressive yield stress, P_y(TS), as a function of total solids concentration of faeces types according to the Bristol Stool Scale (BSS, Table 1) and overlaid thickened waste activated sludge (TWAS) (Skinner et al., 2015). Data points are from settling and filtration tests. The curve fits are obtained from the data points as described in material and methods. Gel point identified as where the line intercepts the x axis.

applied load (i.e. a compressive yield stress) (Usher, 2002). The TS concentration corresponding to ϕ_g therefore signifies the transition between passive sedimentation and mechanical intervention to facilitate compressional stress, and is indicated where each trend intersects the x-axis (Fig. 2). When subjected to an applied compressive pressure, the P_y(TS) of fresh faeces increased significantly with an increase in TS concentration on this semi-logarithmic plot (Fig. 2, Table S3). To illustrate, P_y(TS) were recorded for faeces characterised as BSS4 of 50, 120 and 300 kPa at TS concentrations of 35, 40 and 49% respectively. This demonstrates the maximum solids concentration that can be achieved at these pressures. This can be explained by the increase in volume fraction (in this plot represented by TS), which increases the number of interparticle linkages, and as such the P_y(TS) until it reaches an equilibrium with the applied pressure (Harbour et al., 2001). The compressive yield stress values of the different fresh faeces were compared at a fixed applied compressive pressure (50 kPa) (Fig. 3a), and a strong correlation between P_y(TS) for fresh faeces and the initial faecal solids concentration was identified. The initial solids concentration is in turn broadly related to BSS (Lewis and Heaton, 1997) and appears also to inform on the ϕ_g (Fig. 3b). This correlation is intuitive, as the compressive yield stress is a direct measure of the strength of the bonds between particles in a flocculated suspension under pressure (Green et al., 1996). Whilst TWAS displays higher P_y(TS) than faecal material within the lower TS range, due to the lesser ϕ_g, P_y(TS) at higher TS concentrations are broadly comparable to P_y(TS) of the BSS4. It was observed that the compressive yield stress exhibited by BSS4 at higher TS concentrations, was lower than for BSS1–3 and BSS6 (Fig. 2). The BSS4 structure represents the transition between these two sample types, exhibiting the structure of BSS1–3, with consolidating properties more comparable to BSS6. This synergy providing easiest passage through the human gut. We suggest these preferred material properties maybe responsible for the lower material strength for BSS4, but this would require a more quantitative and specific study of material rheology and chemical analysis to provide such confirmation.

The hindered settling function (R(TS)) is the hydrodynamic resistance to flow of liquor through a particulate suspension as a function of solids volume fraction (herein plotted as TS, Fig. 4a and 5b). For lower TS concentrations (<20% TS), faeces characterised by a more consolidated structure (BSS1–3) exhibited a comparatively low R(TS) whereas, a considerably higher R(TS) was identified for BSS4–6. To illustrate, an R(TS) of 1×10^8 and 3×10^9 kg s^{-1} m^{-3} was recorded for BSS1–3 and BSS4 respectively, corresponding to a TS concentration of 10%. The hindered settling function can be interpreted as either particle transport through a liquid or liquid past a collection of particles and is thus applicable to the

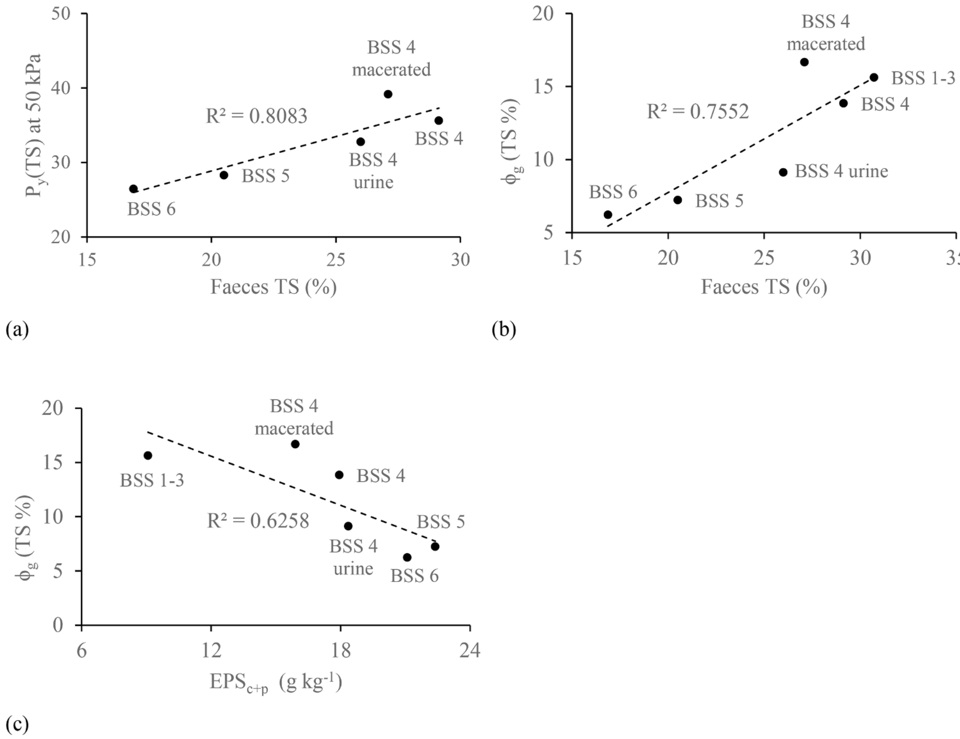


Fig. 3. Effect of faecal solids fractions on compressive yield stress expressed as (a) equilibrim (P_y) total solids concentration (TS,%) at $P = 50$ kPa, (b) faecal starting solids on gel point (ϕ_g) formation and (c) EPS on gel point (ϕ_g) solids concentration.

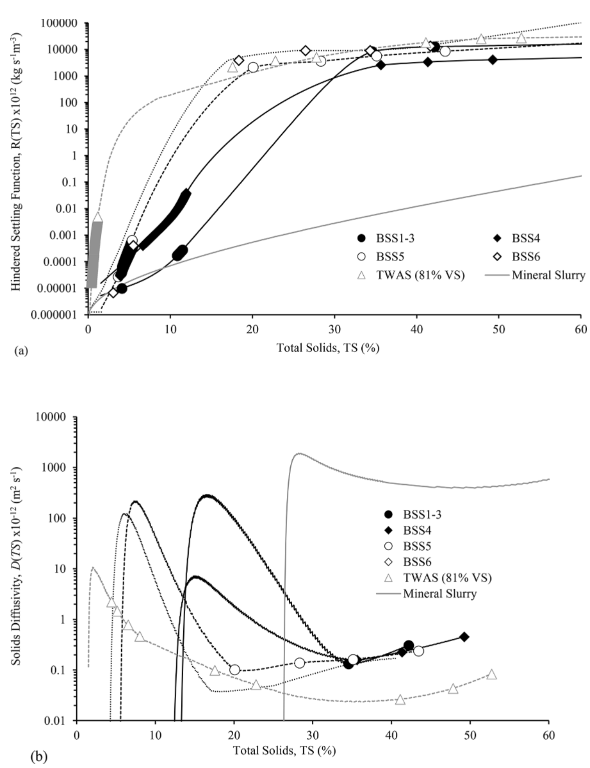


Fig. 4. Compressional rheology behaviour expressed as (a) hindered settling function, R(TS) and (b) solids diffusivity, D(TS), as a function of total solids concentration of faeces types according to the Bristol Stool Scale (BSS, Table 1) and overlaid thickened waste activated sludge (TWAS) (Skinner et al., 2015) and mineral slurry (Usher et al., 2013). Data points are from settling and filtration tests. The curve fits are obtained from the data points as described in material and methods.

full range of solids concentrations from very dilute to very concentrated suspensions (Usher, 2002). The R(TS) for TWAS was markedly higher than fresh faeces, within a considerably more dilute range, indicating that this more disperse suspension exhibits more resistance to flow. The resistance to flow experienced with waste activated sludge has been postulated to arise from interstitial water, water physically and chemically bound in cells and cell structures (e.g. EPS) in addition to more complex colligative properties (Christensen et al., 2015). A comparable gradient in R(TS) versus TS to TWAS was identified within the lower TS concentration range for the more disperse faecal suspensions (BSS4–6), where such structural characteristics are acknowledged to hinder both settling and filterability (Christensen et al., 2015). This agrees with the hindered passive sedimentation of fresh faeces, where a negative correlation between EPS and ϕ_g was observed (Fig. 3c), although further investigation is required to discern the impact of EPS from that of undigested food products. For each organic suspension, a plateau in R(TS) was reached at TS concentrations of 20 to 30%, corresponding to between 1×10^{15} and 1×10^{16} kg s^{-1} m^{-3}. Mineral slurry (Bauxite residue) data obtained from Usher et al., (2013) was overlaid to compare with a less complex and more homogenous suspension. The mineral slurry ϕ_g solids concentration was distinctively higher at 27.6% TS, and an R(TS) of less than 1×10^{11} kg s^{-1} m^{-3} was determined at 50% TS.

Diffusivity (D) combines the competing effects of compressibility and permeability into a single term, to fully characterise filtration when gravitational forces are no longer significant (Harbour et al., 2001; Usher, 2002). The initial sharp phase of the slope corresponds to batch settling, with the secondary phase of the slope related to the applied compressive pressure leading to cake filtration and subsequently compression (Fig. 4b and 5c). For fresh faeces, the D(TS) gradient is generally positive above 20 kPa applied compressive pressure, with extended cake formation and truncated cake compression. Mineral slurry filtration exhibits comparable behaviour, where the D(TS) gradient is positive and filtration curves exhibit extended cake formation with high average solids concentrations close to the equilibrium concentrations enabling relatively truncated cake compression (de

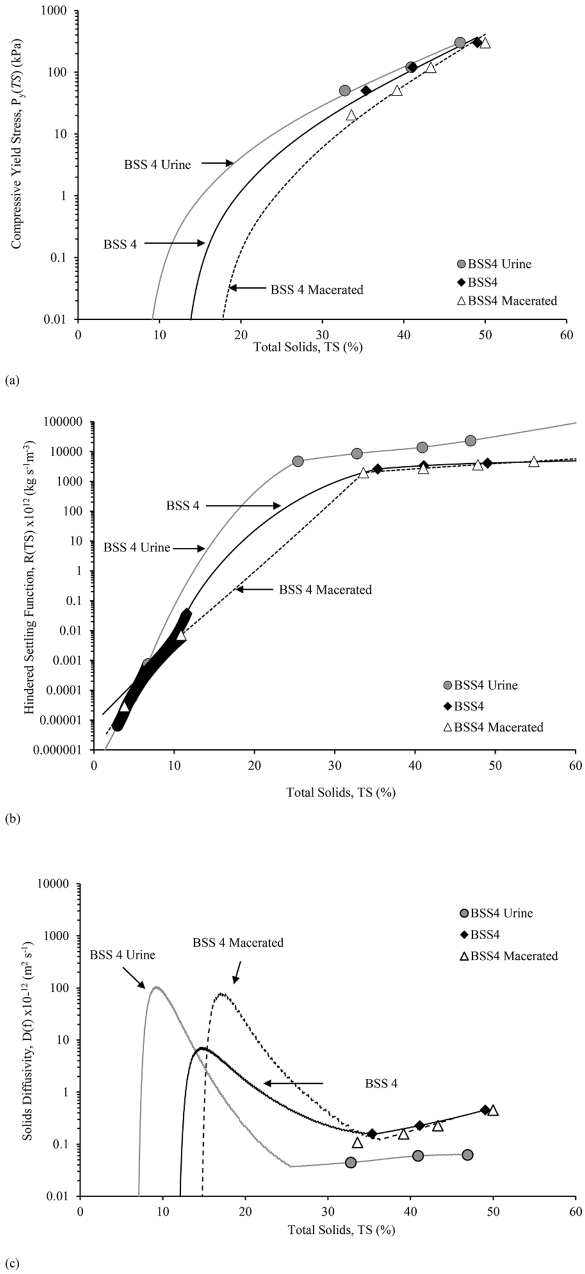


Fig. 5. Compressional rheology behaviour expressed as (a) compressive yield stress, $P_y(TS)$, (b) hindered settling function, R(TS) and (c) solids diffusivity, D (TS), as a function of total solids concentration of faeces type 4 (BSS 4), BSS diluted with urine or BSS 4 macerated. Data points are from settling and filtration tests. The curve fits are obtained from the data points as described in material and methods. For Fig. 5a, gel point identified as where the line intercepts the x axis.

Kretser et al., 2001; Stickland, 2015; Usher et al., 2001). This contradicts filtration behaviour of TWAS, which was characterised by a considerably lower D(TS) indicative of a less dewaterable suspension. More specifically, at pressures corresponding to the region of decreasing D (TS), dewatering was relatively slow near the membrane, causing the filter cake to form at a lower average solids concentration that fills the cavity relatively soon, after which an extended compression phase begins. This is characteristic of organically rich municipal wastewater sludges, dairy effluent and algal biomass (Scales et al., 2004; Skinner et al., 2015; Stickland, 2015; Stickland et al., 2008; Studer, 2008; Wall, 2008). Skinner et al. (2015) hypothesised that the extended compression zone characteristic of TWAS and primary sludge, is attributed to the extensive cross-linked polymeric network in which cellular and particulate components are embedded. The EPS fraction is up to 80% of wastewater sludge (activated sludge) biomass (Neyens and Baeyens, 2003). This results in a compressible and impermeable layer forming on the membrane surface during filtration, which prevents a homogeneous solids gradient during cake formation and causes a-typical non-linear behaviour during water expulsion, until $P_y(TS)$ equilibrium is reached. For comparison, biomass constitutes up to 50% of fresh faeces (Rose et al., 2015).

3.2. Impact of urine and maceration on faeces dewaterability

Fresh faeces are a heterogeneous mixture that in addition to comprising of bacteria and cellular material (as the dominant organic fraction), are also comprised of undigested food residue (i.e. fibre) and an inorganic salt fraction (Penn et al., 2018). Un-masticated food particles present a unique challenge owing to their macroscopic scale (>5 mm) and ability to disrupt the networked structure. Suspension conductivity from enteric salts or downstream mixing with urine, as in decentralised infrastructure such as pit latrines, have been reported to negatively influence the dewaterability of aged faecal sludge (Semiyaga et al., 2016; Ward et al., 2017, 2019). The significance of these unique properties to dewatering was therefore studied using fresh faeces characterised as BSS4 (Table 1) and having a TS concentration of 13.9% at ϕ_g.

The addition of urine slightly reduced ϕ_g to 9.1% TS, and as such a higher $P_y(TS)$ is exhibited by fresh faeces mixed with urine ($BSS4_{urine}$) versus fresh faeces (BSS4, Fig. 5a). At higher solids concentrations (>30% TS) and applied pressures (>20 kPa), the difference in $P_y(TS)$ between $BSS4_{urine}$ and BSS4 becomes less apparent. To illustrate, a $P_y(TS)$ of 300 kPa was observed at TS concentrations of 46.9 and 49.0% for $BSS4_{urine}$ and BSS4 respectively. For suspensions characterised by TS concentrations $\leq \phi_g$, similar values for R(TS) were recorded for $BSS4_{urine}$ and BSS4 (Fig. 5b). However, once compressive pressure is applied to overcome $P_y(TS)$ for TS concentrations $\geq \phi_g$, the presence of urine introduces a greater hydrodynamic resistance, which in turn reduces the overall diffusivity compared to BSS4 (Fig.s 5c). Whilst the D(TS) curve for $BSS4_{urine}$ was characterised by a comparable trend to other fresh faeces, a lower gradient for the positive fraction of the D(TS) slope was observed, resulting in a diffusivity of around an order of magnitude lower at an applied compressive pressure of 300 kPa. Analysis of the liquid faecal liquor fraction and urine determined comparable conductivities of 12.6 mS cm^{-1} and 13.04 mS cm^{-1} respectively (Table S1 and S2). However, when combined with faeces during preparation, the conductivity increased to 14.56 mS cm^{-1}, comparable to conductivities reported for aged public toilet faecal sludge (Ward et al., 2019). Whilst divalent cations are recognised to improve dewaterability through encouraging bridging (Yin et al., 2004), urine is dominated by monovalent ions (e.g. Na^+) (Putnam, 1971), which are known to reduce dewaterability (Christensen et al., 2015). The increased R(TS) of $BSS4_{urine}$ could therefore be attributable to the increase in faecal liquor dissolved solids (3.4 wt.% DS), which negatively impacts permeability (Usher, 2002). Importantly, the ϕ_g, filtration and compression characteristics of $BSS4_{urine}$ can still be regarded as more favourable than conventional wastewater suspensions, managed through dewatering with centralised infrastructure.

Maceration was applied to disrupt undigested food particles (e.g. fibre), the effect of which was a shift in the distribution of coarse particles from the >4.75 mm fraction to the ≤ 1 mm size fraction, as demonstrated by an increase in the ≤ 1 mm size fraction from 44 to 60% on a weight basis (Fig. S2). Maceration was observed to reduce the compressive yield stress, relative to BSS4, whilst the impact of maceration on permeability (R(TS)) was less evident. This is comparable to observations by Semiyaga et al. (2016), where particles greater than 1 mm correlated negatively with the extent of dewatering for faecal sludge from unlined pit latrines. At higher applied pressures, D(TS) for

$BSS4_{maceration}$ is similar to BSS4 (Fig. 5c). The reduced difference for high applied pressures, where $P_y(TS)$ converges at comparable solids concentrations, could be associated with exceeding the stress required to compress the rigid macro-particles such as seeds and corn kernels even in non-macerated samples. At 300 kPa, maceration only increases the P_y solids concentrations by 0.7% TS, suggesting that high pressure dewatering processes such as filter presses, which typically operate from 500 kPa (Lenntech, 2020), can negate the requirement for maceration pre-treatment for improved dewaterability at higher solids concentrations. However, maceration was observed to introduce critical structural transformation at lower TS concentrations and applied compressive pressures. This was evidenced by an increase in ϕ_g from 13.9% to 16.7% TS (Fig. 5a), which indicates that maceration maybe beneficial for improving faecal material thickening processes.

3.3. Modelling dewatering processes

A range of initial solids concentrations (TS = 0.1, 1, 3, 10 and 25% w/w) were used with initial saline diluted faeces heights that scaled to ensure all scenarios used the same amount of solid material (nominally 1 cm at 35% TS). For the passive gravity thickening process, 1, 3 and 10% TS were selected as representative of TS concentrations encountered downstream of a toilet accepting urine, faeces and flush water collectively; urine and faeces only; and the average faeces ϕ_g respectively (Fig. 6a, Table S4). A scenario with 25% initial TS concentration was excluded from the passive gravity thickening modelling as this is beyond the gel point observed for faecal material and hence unattainable by passive gravity thickening. For fresh faeces (BSS4, Table 1), initial TS concentrations of 1 and 3% achieve a TS concentration comparable to the gel point (around 10%) within around 30 min, with the 3 and 10% initial TS concentrations consolidating to a final concentration of 14% TS after 1 day. The 1% initial TS concentration consolidates to the same TSS concentration, but a lower TS concentration due to the lower DS concentration imposed by flush water dilution. In comparison, it takes more than 10 days to settle and consolidate from 1 to 2% TS secondary treatment waste activated sludge (TWAS), due to the lower gel point and slower settling rate.

For centrifugation, initial TS concentrations of 3 and 10% were selected for fresh faeces assuming an initial settling stage. The centrifuge conditions were 1000 rpm with a 0.25 m outer radius (Fig. 6b, Table S4). Faeces settle to form a sediment at or above ϕ_g after 1 h and then consolidate to a final concentration of 19% TS in around 12 h, irrespective of the initial solids concentration. For reference, the TWAS was characterised by an initial TS concentration of 3%, consolidating to 5% but over a prohibitive timescale of >10 days. Higher centrifugation rotational speed was demonstrated with fresh faeces operated at 3000 rpm, and increased dewatering rate by a factor of 10 and to a higher TS concentration of 25%. In comparison to the organic matrices, the mineral slurry is able to reach to a final solids concentration of 52% TS in <1 min.

When subjected to pressure filtration at 300 kPa, fresh faeces can form a cake of ~50% TS, as observed experimentally (Fig. S3). Modelling experimental results determined that after 5, 8, 17 and 550 days, 50% TS can be achieved for starting TS concentrations of 25, 10, 3 and 0.1% respectively (Fig. 6c, Table S4). A value of 0.1% TS was utilised as an example of urine and faeces diluted with a significant volume of flushwater, which coincides with TS (%) in untreated domestic sewage (Metcalf and Eddy, 2013). This demonstrates the importance of a two stage dewatering intervention for this permeability limited process, where an initial solids/liquid separation close to source could reduce capital scale, cost and energy demand of a second centralised dewatering unit. To illustrate, in order to reach 25–35% TS, an increase in initial TS from 3% to 10% (approaching ϕ_g) decreases filtration time by a factor of 2–10. Due to the reduced scale of decentralised infrastructure, using pressure filtration with hold times of several days may not be prohibitive for implementation. However, higher pressures are often applied for

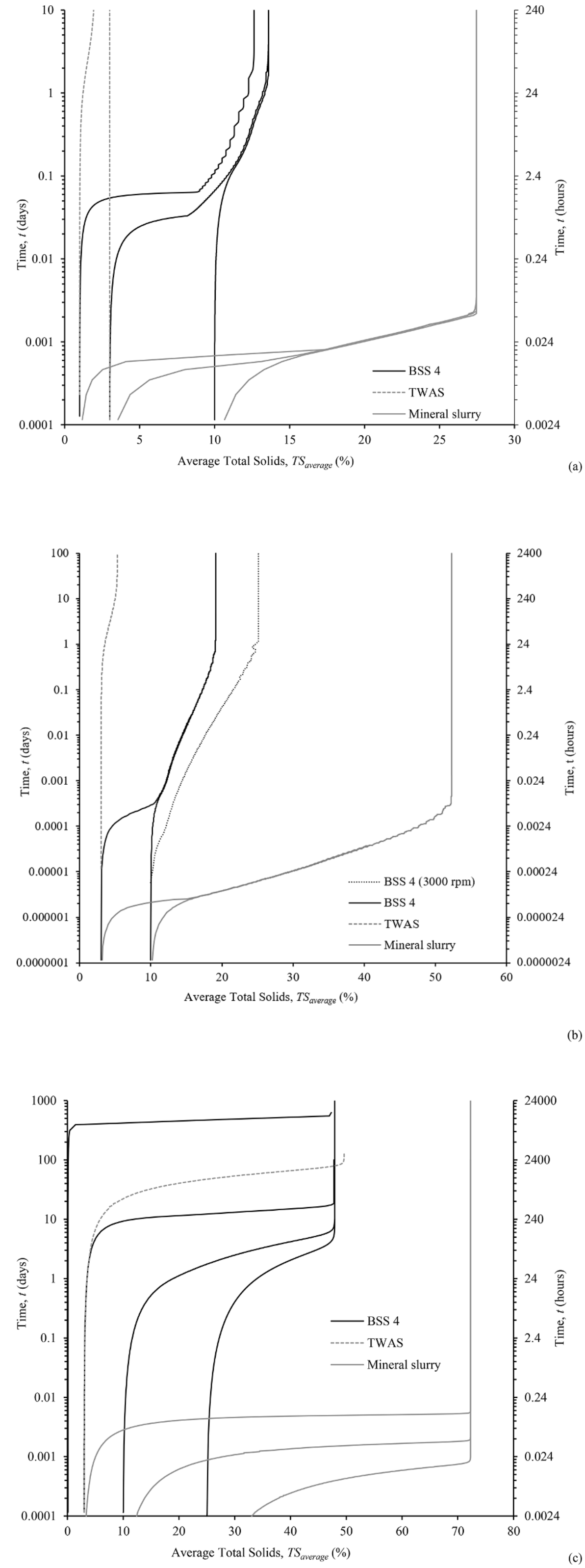


Fig. 6. Modelled batch dewatering scenarios comparing faeces (Bristol stool scale 4, BSS 4), wastewater sludge (thickened waste activated sludge, TWAS) and mineral slurry. (a) Gravity settling, (b) centrifugation at 1000 rpm with a 0.25 m outer radius and (c) pressure filtration operated at 300 kPa. Dewatering commences at 0.1, 1, 3, 10 and 25% TS where practical with initial heights that scale to ensure that all scenarios use the same amount of solid material (nominally 1 cm at 35% TS). Wastewater sludge dewatering properties sourced from Skinner et al. (2015) and mineral slurry data from (Usher et al., 2013).

typical filter presses (500–1500 kPa, Lenntech, 2020), an increase of which could assist in reducing hold-up time.

4. Outlook: impact of human faeces rheology on dewatering

To the best of our knowledge, fresh faeces is the only known organic wastewater matrix to exhibit elongated cake filtration coupled with short compression. This indicates that a high solids concentration product can be achieved within a shorter time frame. This may be explained by the shear and compression history of faeces, as they have been subject to effective compression and dehydration by the colon before discharge (Lewis and Heaton, 1997). Shear and compression history are known to influence network strength and as such the $P_y(TS)$ of the matrix (Green et al., 1996). This is opposed to observations reported for wastewater sludge (TWAS and primary) (Skinner et al., 2015), and may result from different structural properties of fresh faeces, with more compact aggregates known to advantage dewaterability (Christensen et al., 2015). When subject to viscous shear, as in the case of piped sewerage transport to a centralised works, aggregate erosion occurs, increasing single cell number and reducing particle size that has been demonstrated to reduce permeability. Sludge storage in anaerobic conditions, has been shown to inhibit dewatering due to the apparent hydrolysis of bound EPS (Christensen et al., 2015). These irreversible structural changes occurring during transport and storage may help explain why a lower gel point and different dewatering behaviour are observed for wastewater sludge and faecal material (Fig. 2, 4) that are ultimately of similar organic origin.

5. Conclusions

The compressional rheology of fresh faeces has been characterised to determine whether earlier dewatering can improve decentralised sanitation:

- The gel point for fresh faeces ranged between 6.3 and 15.6% TS concentration, which is significantly higher than for wastewater sludge at centralised facilities. This implies that the use of passive (gravity driven) separation for fresh faces, can produce a concentrated matrix and reduce transportation volume.
- Modelling confirmed the efficacy of gravity driven separation, with thickening from 3 to 10% TS concentration requiring <0.5 h. This is significant, as it suggests that a 70% reduction in water content can be achieved using simple, low-cost technology that could be applied at community or even single household scale.
- Rheological characteristics of dewatering such as gel point and compressive yield stress, could be broadly related to Bristol Stool Scale. Further research to decouple the impact of EPS originating from undigested food products from those of faeces, could also provide insight into the differentiation observed.
- Similar to centralised wastewater sludge, an increase in EPS content resulted in network onset at lower total solids concentrations. However, when subjected to mechanical filtration, benefits of handling fresh faecal material were observed, with a more concentrated cake formed in a shorter time period. This is supported by modelling, which illustrated that initial thickening with 300 kPa filtration could achieve a 1.4 cm thick 25% TS product in <24 h.

Such performance is only enabled by the unique kinetic and compressive yield stress properties of fresh faeces, which if used to inform localised dewatering, could change the practical and economic viability of community scale faecal solids management. Further research to elucidate the ageing profile of faeces in terms of compressional rheology would be beneficial to identify the trade-off between storage and dewaterability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2021.117526.

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